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An Announced Extinction: The Impacts of Mining on the Persistence of *Arthrocereus glaziovii*, a Microendemic Species of Campos Rupestres

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Abstract: The mountaintops of eastern Brazil harbor the highest rates of plant endemism in South America. However, local biodiversity faces constant threats due to habitat loss and mining activities. About 89 rare and endangered species are exclusive to this region, including the threatened species *Arthrocereus glaziovii*. This study aims to evaluate the potential distribution of *A. glaziovii* based on abiotic variables and soil elements and to characterize the distribution of mineral titles that may restrict the species' occurrence areas. We used the Bioclim, Domain, MaxEnt, GLM, and Random Forest algorithms to model this ecological niche under future climatic scenarios, in addition to modeling the layers of mineral titles corresponding to areas already mined and those slated for future mining projects. Our predictions indicate an expansion in the future distribution of *A. glaziovii*. Nevertheless, the future predicted occurrence areas of the species are already compromised due to mining. According to our findings, we emphasize the looming threat of the predicted extinction of this species. Therefore, implementing conservation strategies to ensure the survival of *A. glaziovii* is imperative.

Keywords: ironstone rupestrian grasslands; Cactaceae; geographic distribution; conservation; red list

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1. Introduction

Brazil is the second-largest mineral producer in the world [1]. Thus, mineral extraction is one of Brazil's most important economic activities, mainly in the eastern Brazil mountaintops, which encompasses the threatened rupestrian grassland (hereafter, *campo rupestre*) [2]. The *campo rupestre* is characterized by a rich mosaic of herbaceous vegetation and sparse shrubs [3]. The region's soil is compact, deficient in water and nutrients, and high in heavy metals [4,5].

The rocky outcrops in the *campo rupestre*, particularly the iron ones (hereafter, *canga*), are rich in endemic plant species and substantially contribute to the biodiversity of the domains in which they are inserted, namely the Cerrado and Atlantic Forest [6,7]. These plants evolved on extremely nutrient-poor soils [8] and are adapted to distinctly seasonal climates [9]. Plants from these locations are very susceptible to soil removal [10]. They have a limited dispersal distance and slow growth [11], hindering the natural regeneration of altered *campos rupestres* [12]. It has recently been observed that the combination of this edaphic endemism and limited seed dispersal threatens the persistence of these mountaintop species [13].

Vegetation in the *campo rupestre* is highly threatened due to its restricted area [14] and the climate changes forecasted for the future [15], making their conservation extremely important, urgent, and necessary. The climate change scenarios predicted suggest catastrophic consequences for this ecosystem [15], and models project a reduction of up to 95% in the *campo rupestre*'s current suitable area [16].

In addition to the threats mentioned above, there is a high mining pressure in this ecosystem [11] since we find in the *campo rupestre* one of Brazil's largest iron ore extraction areas, the Iron Quadrangle (local name *Quadrilátero Ferrífero* (Q.F.)), placing mining as the main factor of destruction in this region [17]. From 1960 to 2012, the Q.F. lost about 40% of its total area of *cangas* (about 100 ferruginous outcrops) to iron ore extraction [7,17]. Today, there are nearly 225 remaining ferruginous outcrops, and 83% of these show signs of loss or degradation by mining [7].

The Q.F. is the central mineral-producing province in the world in terms of iron ore [18,19], and the loss of species from mining activities is marked by a high, irreversible environmental impact [20]. The intense mining activities practiced in the area since the early 17th century on a large scale [21] continue to impact the flora of the *campo rupestre*, resulting in areas with exposed subsoil or gravel, which, even after decades, no natural recovery has been recorded [22]. In addition, about 89 rare and threatened species in the Q.F. are plants with high conservation value, occurring exclusively in *cangas* in the region [17]. One of these species on the mountaintops of rocky fields impacted by mineral exploration is the microendemic and endangered cactus *Arthrocereus glaziovii*, which has suffered from a reduced area of occurrence [14,23].

In this study, we predicted the potential and future geographical distribution of *A. glaziovii*, an exclusive, threatened, and rare species of the *campo rupestre*. Specifically, we (i) study the potential distribution of *A. glaziovii*, based on abiotic variables and soil elements, to understand the impacts of these climatic variables in the future distribution of the species and its ecosystem and (ii) characterize the distribution of mineral titles that may restrict the areas of occurrence of *A. glaziovii* in order to understand the impact of mining on the potential distribution of the species.

2. Materials and Methods

2.1. Study Species

The Cactaceae family is neotropical, distributed almost exclusively on the American continent, and its main center of diversity is East Brazil [24,25]. Cacti have been the subject of diverse studies since they are used as food, fodder, medicinal, and ornamental plants. Thus, the Cactaceae family has always sparked interest because of their morphological peculiarities and chemical properties [25,26]. The highest biodiversity is observed in arid and semi-arid regions, where cacti serve as crucial resource reservoirs for numerous species of vertebrates and invertebrates, particularly during droughts characterized by resource scarcity [26].

The genus *Arthrocereus* stands out among the Cactaceae family, comprising six species, all endemic to Brazil. They occur in shrub and sub-shrub forms and have particular habitats. Consequently, they are restricted to their localities [27]. *Arthrocereus glaziovii* (K. Schum.) N. P. Taylor & Zappi is among the three taxa of this genus present in Southeastern Brazil and stands out as a rare columnar-looking cactus. The species is considered microendemic, as it has few populations restricted to the ferruginous outcrops of the *campos rupestres* [28]. This cactus is considered threatened with extinction, according to the International Union for the Conservation of Nature (IUCN) [29], due to anthropogenic activities which cause the suppression of its habitat by removing soil for mining [30]. The species is considered a priority in the recovery of the ferruginous rocky fields of the Q.F., as it is unique to the region [31].

2.2. Study Area

Considering that the microendemic distribution of the species manly occurs in places rich in iron ore, the study region is concentrated in the Espinhaço Range, a mountain range characterized by the dominance of diverse and abundant rupestrian grasslands, where the Q.F. is located. The Espinhaço Range is situated within the Brazilian Central Plateau and stands as one of the most significant mountain ranges in the country, boasting one of the highest levels of floristic diversity in South America [4,9,32,33].

In the large iron ore deposits of the mountain ranges that delimit the Q.F., this is where the ferruginous outcrops, known as *cangas*, are located [14]. The *cangas* are composed of interspersed quartzitic, granitic, and hematitic outcrops, forming different microhabitats where *A. glaziovii* occurs [30] (Figure 1). With the region's climate being considered as high-altitude subtropical (dry winters and wet summers), according to the Köppen climate classification [34], the *campo rupestre* presents daily high thermal amplitudes (minimum of 14.1 °C and maximum of 23.7 °C) and low relative humidity [30,35]. Thus, soil, relief, and climate conditions are the main factors for establishing its unique and dominant vegetation cover [36].

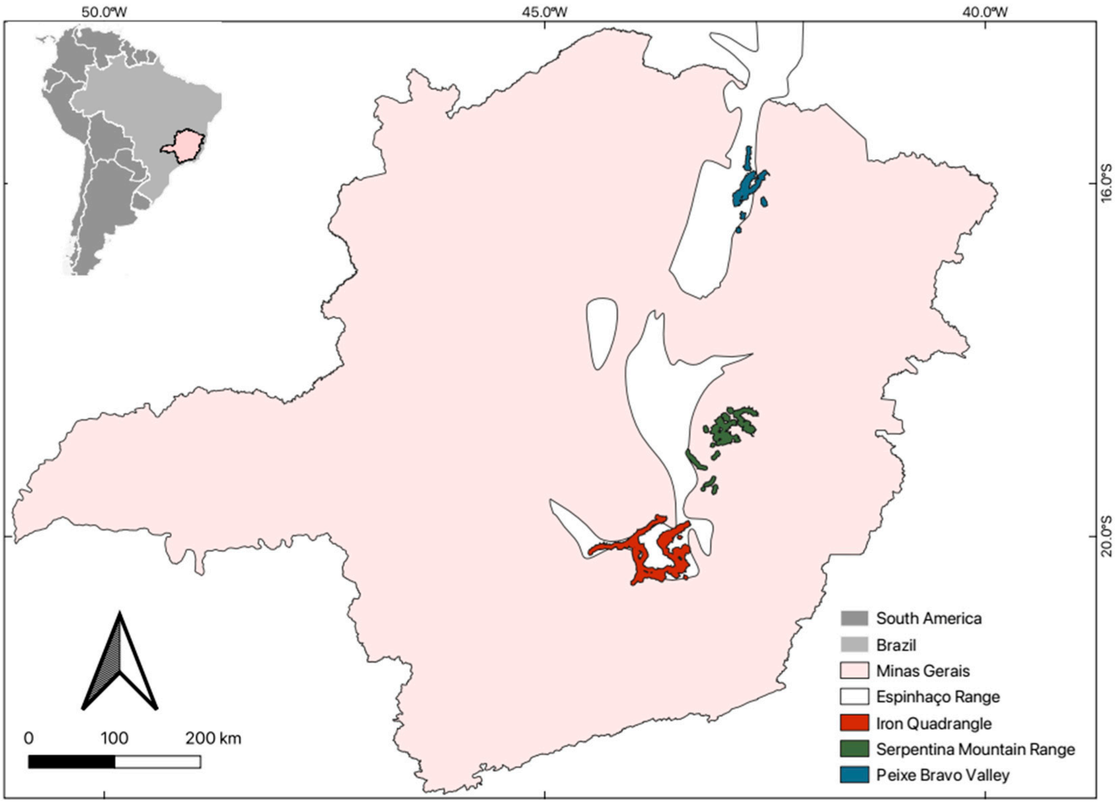

Figure 1. Regions of occurrence of *cangas* in the Minas Gerais state. Source: Pristino Institute.

This region supplies the demand for iron ore in Brazil and abroad. The annual Brazilian iron ore production is approximately 400 million tons, and more than half of this production is concentrated in the Q.F. [37]. In 2019, the iron ore production of the largest Brazilian mining company, and third in the world, located in Minas Gerais state (M.G.), was 301.9 million tons [38].

2.3. Species Distribution Modeling

To determine the ecological niche of *A. glaziovii*, we collected georeferenced specimen records from the Global Biodiversity Information Facility (GBIF) [39], from *species*Link databases [40], from the herbarium from the Federal University of Minas Gerais (UFMG), and from literature data [41]. Records containing wrong geographic coordinates, no coordinates, or incomplete data were excluded from our analysis.

We used ecological niche modeling (ENM) to model the potential distribution of *A. glaziovii* in the Minas Gerais state region, which comprises a large part of the Espinhaço Range, including the Q.F. For the modeling, we use five types of ENM algorithms. It is essential to use several algorithms to ensure the prediction is as accurate as possible. Each method has a different predictive ability, degrees of complexity, and stability, generating different responses for each variable. The algorithms were applied to all compiled georeferenced record points (Figure 2; Table S1).

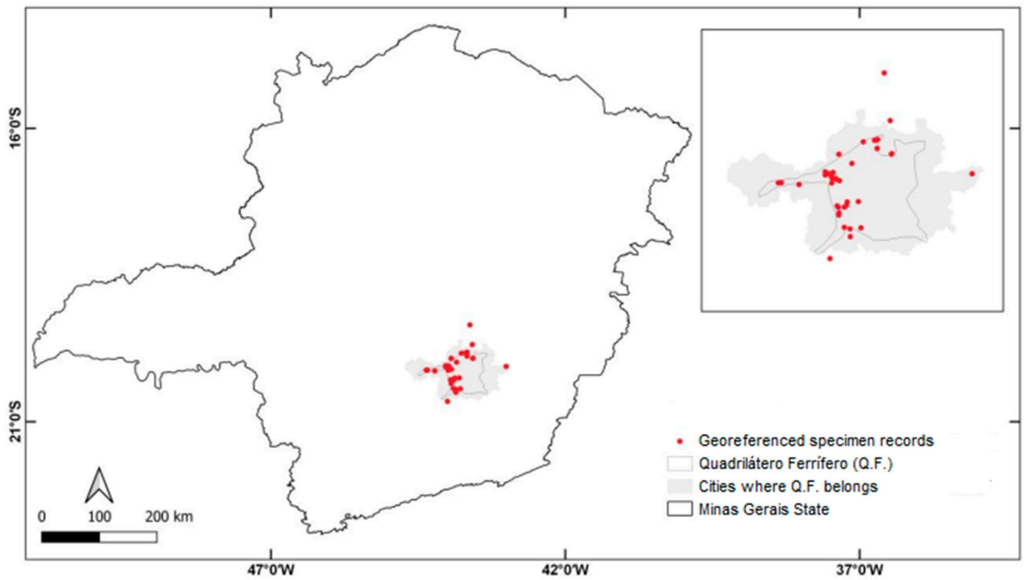

Figure 2. The location of the studied species, *Arthrocereus glaziovii* (red circles indicate the occurrence locations used for ecological niche modeling).

2.4. Climatic and Edaphic Data

We compiled two sets of variables for constructing ENMs: climatic and edaphic. For climate models, we used solar radiation and the 19 bioclimatic variables (Table S2) developed by [42], available on Worldclim 2020 [43]. Specifically, we used annual mean temperature (BIO1), mean diurnal range (BIO2), isothermality (BIO3), temperature seasonality (BIO4), maximum temperature of warmest month (BIO5), minimum temperature of coldest month (BIO6), temperature annual range (BIO7), mean temperature of wettest quarter (BIO8), mean temperature of driest quarter (BIO9), mean temperature of warmest quarter (BIO10), mean temperature of coldest quarter (BIO11), annual precipitation (BIO12), precipitation of wettest month (BIO13), precipitation of driest month (BIO14), precipitation seasonality (BIO15), precipitation of wettest quarter (BIO16), precipitation of driest quarter (BIO17), precipitation of warmest quarter (BIO18), precipitation of coldest quarter (BIO19), and solar radiation (srad). These variables were constructed based on the spatial extrapolation of monthly averages of climate, temperature, and precipitation data collected from meteorological stations worldwide between 1970 and 2000. For the edaphic models, we used 18 soil variables (Table S3) obtained from Instituto Brasileiro de Geografia e Estatística (IBGE) [44], specifically aluminum saturation (Alsat), aluminum (Al), sand, clay, base saturation (Bsat), base sum (Bsum), calcium (Ca), organic carbon (C), cation exchange capacity (cec), exchangeable hydrogen (H), magnesium (Mg), natural organic matter (om), nitrogen (N), water ph (pHwater), KCl ph (pHKCl), potassium (K), silt, and sodium (Na). Climatic data were acquired with a resolution of 30 s of arc (1 km^2 spatial resolution), and edaphic data were obtained with a resolution of 2.5 min (5 km^2 spatial resolution). This difference in scale was why we did not perform an overlapping model of climatic and edaphic variables. These datasets were later cut to only cover the state of Minas Gerais.

To avoid redundancy in the variables, we performed a pair-by-pair Pearson correlation for each dataset (climate and edaphic), available in the Raster package [45] of R software 4.3.2 [46]. Only one variable was selected with 70% or more correlation to avoid an excess of autocorrelated variables, following [47]. These chosen variables were submitted to a Random Forest selection, eliminating variables irrelevant to the data and ordering the variables in order of importance. This selection was made using the VSURF package [48].

2.5. Modeling and Evaluation Procedures

To carry out the modeling, we chose five algorithms: Bioclim, Domain Generating Algorithm (DGA), General Linear Model (GLM), Maximum Entropy (MaxEnt), and Random Forest (R.F.), commonly used in ENM analysis.

The Bioclim algorithm [49] is a climate envelope model that calculates similarity in amplitude based on presence–absence. This algorithm compares the values of variables in any location with the values that appear in the grid of species occurrence points to identify locations with better environmental suitability [49]. The Domain algorithm [50] calculates the Gower distance to find the minimal distance between environmental variables at a location and the known locations of occurrence. The General Linear Model (GLM) is a logistic regression model that analyzes cause and consequence, indicating which variables are responsible for the presence or absence of the species. The Maximum Entropy (MaxEnt) model [51] is a machine learning model based on maximum entropy. This method creates random absence points in the background, which, together with the presence points, will determine the possible area of occurrence and restrict the distribution according to the variables [52]. The Random Forest (RF) algorithm [53] is a regression and machine learning model that creates "trees". It groups them to obtain a prediction with greater accuracy and stability. The advantage is that it adds extra randomness to the model without overfitting the data.

As we do not have actual absence points, we created one thousand pseudo-absence points for the studied species to be used in the GLM, MaxEnt, and R.F. models. After analyzing each current model generated by the algorithms, we created a mean between all models in each set (climate and edaphic). We used 80% of the points to construct the models and the remaining 20% of the points for model validation. We used the Dismo package [54] for the Bioclim, Domain, and MaxEnt models and the randomForest package [55] for the RF model. All analyses were performed using R version 3.5.3 software [46].

2.6. Mining Titles

The layers of the mineral titles were obtained in vector format from Instituto Pristino's Geoenvironmental Digital Atlas database [56]. We use 52 layers corresponding to areas that are already mined and those that will be mined in the future.

3. Results

3.1. Selected Climatic and Edaphic Variables

After performing Pearson's correlation, 6 of the 20 initial climatic variables were selected (Tables S4 and S5) and submitted to VSURF. Among these six input climate variables, seasonal precipitation (BIO15), mean annual temperature (BIO1), annual precipitation (BIO12), temperature seasonality (BIO4), and annual temperature variation (BIO7) were the most influential according to the VSURF importance values (Table 1), and solar radiation was not significant (SRAD).

Table 1. Climatic and edaphic variables used as predictors in ENM, in order of importance.

Climatic Variables [1]	Edaphic Variables [2]
Seasonal Precipitation (BIO15)	Silt
Mean Annual Temperature (BIO1)	Potassium (K)
Annual Precipitation (BIO12)	Nitrogen (N)
Temperature Seasonality (BIO4)	Hydrogen (H)
Annual Temperature Variation (BIO7)	Clay
	Sand
	Water pH
	Magnesium

[1] Wordclim. [2] IBGE.

Ten of the eighteen initial soil variables were selected by Pearson's correlation (Table S4) and submitted to VSURF. Among these ten selected edaphic variables, silt, potassium (K), nitrogen (N), and hydrogen (H) were the four most influential, and only aluminum (Al) did not influence the model. After excluding the irrelevant variables, the other variables were classified in order of influence (Table 1).

3.2. Current Potential Environmental Suitability for Arthrocereus glaziovii

All models had an area under the curve (AUC) > 0.98, showing their effectiveness. When considering each of the models individually for both climatic and edaphic variables, together, the most restrictive algorithms for the area were Bioclim and R.F., which identified a small space with environmental suitability located in the Q.F. (Figures 3A,D and 4A,D). Domain and MaxEnt were the algorithms that presented a moderately wide distribution, identifying restricted distributions in the center, south, and southeast of Minas Gerais state and in the mountainous areas of the studied site (Figures 3B,E and 4B,E). The algorithm with the broadest distribution was the GLM, which identified almost every area analyzed with a probability of environmental suitability for both variables (Figures 3C and 4C).

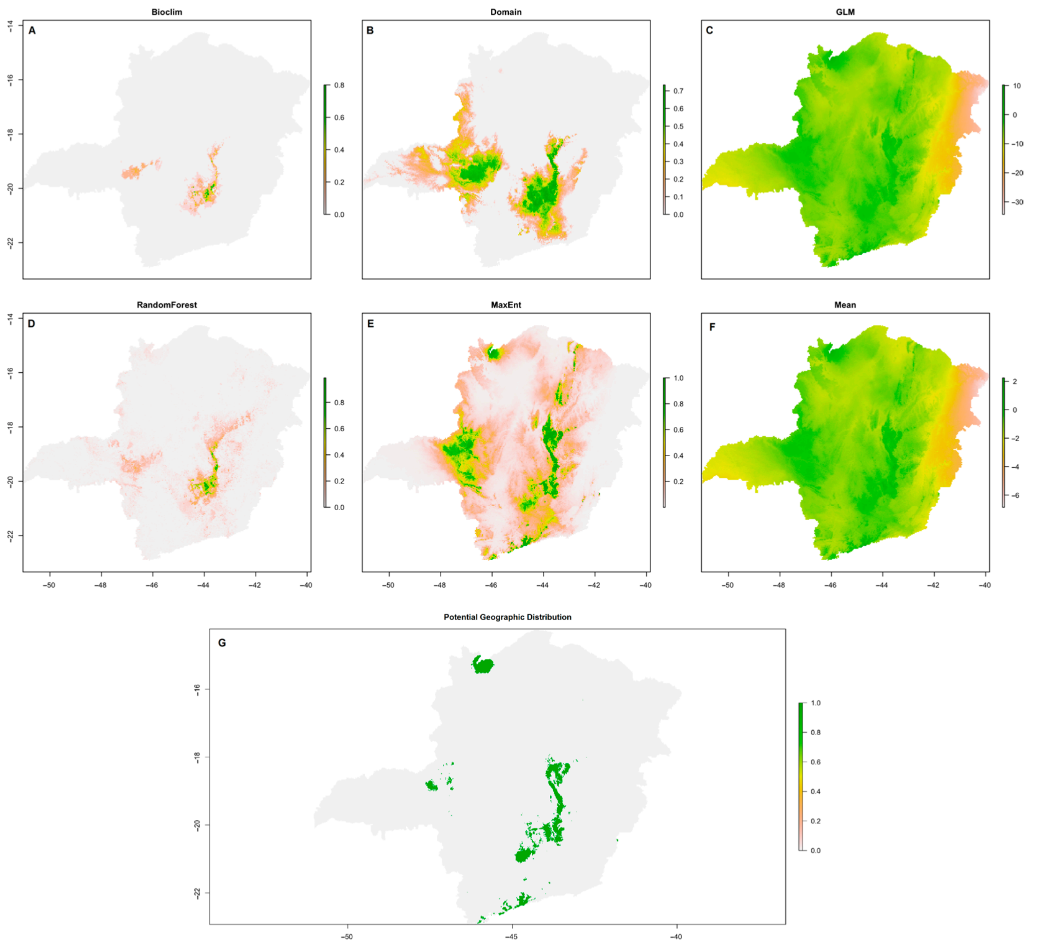

Figure 3. *Arthrocereus glaziovii* prediction models for the climatic variables of the algorithms: (**A**) Bioclim, (**B**) Domain, (**C**) GLM, (**D**) R.F., (**E**) MaxEnt, (**F**) average between all algorithms, (**G**) potential geographic distribution of the species generated from the average of the algorithms.

According to the Bioclim climate model, the average annual temperature allowing for the occurrence of *A. glaziovii* is very restricted (between 16 and 20 °C), with annual precipitation ranging between 1500 and 1600 mm, seasonal precipitation ranging between 84 and 86 mm, the temperature in the hottest month ranging between 18.2 and 19.1 °C, and a variation in annual temperature between 1.7 and 1.8 °C. According to the Domain climate model, the restriction of species occurrence was similar, with a yearly average temperature between 16 and 21 °C, a variation annual precipitation between 1450 and 1650 mm, seasonal precipitation between 82 and 89 mm, the temperature in the hottest month being between 17.5 and 20.1 °C, and a variation in annual temperature between 1.6 and 1.8 °C. For MaxEnt, the most critical climate variable for the niche was the yearly mean temperature, followed by seasonal precipitation, annual precipitation, and annual temperature variation. For this model, the temperature of the warmest month was not significant. As for the R.F., the most essential variable for the niche was annual precipitation, followed by yearly temperature variation, seasonal precipitation, average annual temperature, and temperature of the hottest month.

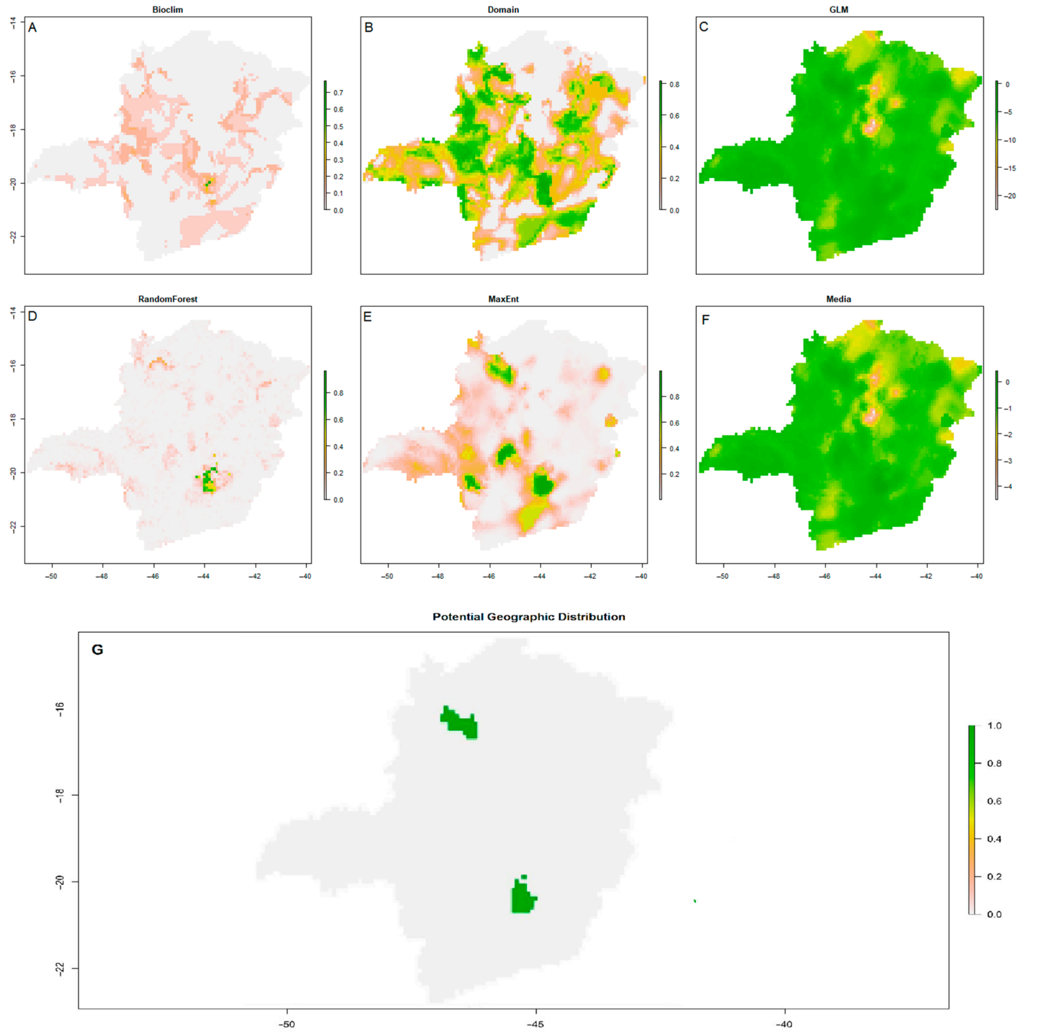

Figure 4. *Arthrocereus glaziovii* prediction models for the edaphic variables of the algorithms: (**A**) Bioclim, (**B**) Domain, (**C**) GLM, (**D**) R.F., (**E**) MaxEnt, (**F**) average between all algorithms, (**G**) potential geographic distribution of the species generated from the average of the algorithms.

Using Bioclim's edaphic model, sand and clay showed high levels, from 41 to 53 and 25 to 27, respectively, followed by silt with 15 to 20, pH at 5, H from 3 to 4, and Mg 0 to 1. Using the Domain model, the soil presented similar or close values, sand presented values between 30 and 60, clay between 15 and 38, silt at 10 to 15, pH at 5, H at 1 to 6, and Mg again at 0 a 1. Nitrogen and K had values equal to 0. For the MaxEnt model, the most critical edaphic variable for the niche was Mg (50%), followed by K, N, clay, and silt. As for R.F., the most essential variable for the niche was the concentration of N, followed by silt, clay, K, and Mg. Sand, H, and water pH were not important in any model.

The average of all models showed a wide potential distribution of the species (Figure 4F). According to the average cut-off of all environmental niche models, the potential distribution of *A. glaziovii* is currently located in the central-southeast and south of M.G., with a particular concentration in the Espinhaço Range (and the Q.F.) and the northern regions, as well as south (Serra da Mantiqueira) and north of the study area (Figure 3G).

3.3. Mining Titles

Overlapping all layers of mineral titles in the Q.F., we observe few remaining mining-free areas in this region (Figure 5). Iron ore extraction is the most frequent mining activity, followed by gold ore extraction. In fact, the Q.F. has numerous deposits of iron and gold ore, which makes the state of Minas Gerais one of the largest producers of these minerals in the world [18]. So, it becomes clear that the distribution of *A. glaziovii*, both actual and potential, is over an essential area for mining extraction. The distribution of future mines largely overlaps current occurrence areas and suitable regions for potential distribution of the species.

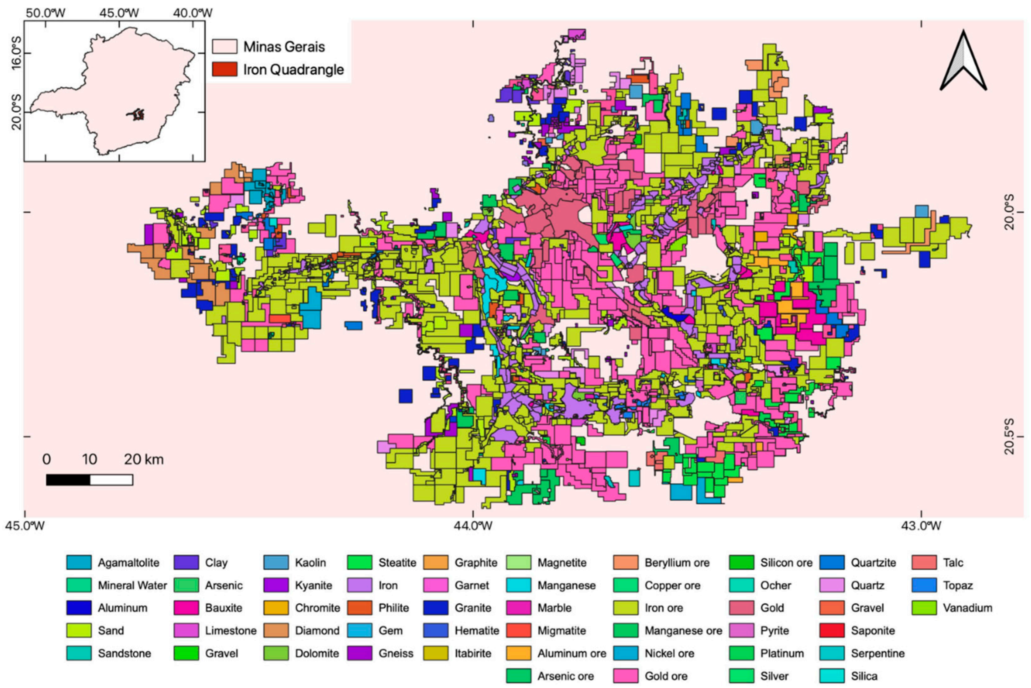

Figure 5. Mining titles currently licensed in the Iron Quadrangle (Q.F.) region. Source: Pristine Institute.

4. Discussion

Our results demonstrate that the potential occurrence area of *A. glaziovii*, considering both climatic and edaphic variables, is larger and covers areas outside the Q.F. However, currently licensed and under-exploration mining titles and areas licensed for future mining activities threaten the entire identified area, jeopardizing the species' survival.

Seasonal and annual rainfall, temperature in the warmest month, and annual temperature were the abiotic factors determining the geographic distribution of *A. glaziovii*. Temperature and rainfall are important, as they influence the length and intensity of the cactus's reproductive period [57]. Precipitation is the primary factor influencing seedling emergence and the survival of cacti. Studies have indicated that spatial and temporal fluctuations in precipitation significantly shape the establishment patterns observed in this family [25]. *A. glaziovii* has an annual flowering period lasting from 1 to 5 months, starting between the end of the dry period and the beginning of the rainy period [58,59]. The temperature positively influences the production of flowers and fruits, but rainfall does not influence this factor [60]. The fruiting of the species takes place in the middle of the rainy season, and both temperature and rainfall positively influence this phenophase [60].

Increases and decreases in temperature influence the germination of the species, with an optimal temperature between 25 and 30 °C, even in the rainy season, needed to establish seedlings [3,61].

The species *A. glaziovii* currently occurs in the Q.F. region in the center-southeast of the Minas Gerais state, and the Domain and MaxEnt models indicated a potentially larger distribution area for this species in this same region. The Bioclim and R.F. models showed a minor occurrence compared to the current model. The GLM indicated a wide distribution throughout the Minas Gerais state. The cut of the averages of the models stated an occurrence area located to the south (climate model) and north of the state of Minas Gerais. The potential distribution models of *A. glaziovii* showed, therefore, that this species has a potential geographic distribution restricted to the central-southeast region of the Minas Gerais state, with a concentration along the Espinhaço Range, to the south and north of this state.

The south area of Minas Gerais state in the climate models is called Serra da Mantiqueira, and its indication in the model is probably due to it being a region with high elevations. According to Koppen's classification, the climate in this region is subtropical in altitude, equal to that of the species' current occurrence area [62]. In Serra da Mantiqueira, the vegetation found is called campo de altitude. It grows under granitic outcrops of igneous or metamorphic rocks, which differ from the physiognomies occurring on the *cangas* of the Q.F. and the quartzite fields of the Espinhaço Range [62]. Although both occur on rocks and have similar climates, they are of different lithotypes, explaining why the edaphic model did not point to this region [62].

Only the MaxEnt model of climate variables indicated a small area in the north of Minas Gerais state as a possible area of environmental suitability for the occurrence of *A. glaziovii*. This region is a transition area of Cerrado and Caatinga domains with hematite in the soil and a humid tropical savannah climate. The driest season coincides with winter, and rainfall is less than 60 mm [63]. The soil of this indicated region also presents high concentrations of Fe, as seen in the areas of occurrence of the species in the Q.F. However, this element was not analyzed in the models, as no studies prove its direct influence on the plant, indicating that the species has some mechanism of accumulation or tolerance to it [41].

Furthermore, the indication of the area in the north in the edaphic models is due to other elements of its composition. For the studied species, Mg, K, N, silt, and clay were the most important elements in determining the distribution model of its edaphic variables. K has a positive correlation with the development and growth of *A. glaziovii* and can promote its germination. At the same time, N in large concentrations decreases the germination rate of the species [41]. Sand and clay contents are directly related to the water retention capacity of canga soils [64]. The soil of the northern region has high Mg levels, oscillating between high and low K, which would contradict the preference found in our results. However, it has high values of silt, with 50% (high) of its composition being clay and 20% (low) being sand, and the pH of the area is slightly acidic, between 5.8 and 6.6, which explains the indication of this area in the model [65].

The overlapping of existing mining titles in the Q.F. indicates that the remaining areas of the *canga* are entirely compromised by mining, and mining activity tends to always increase and surpass past production levels. In addition, the mining lobby has considerable influence in Brazil country [66], and the Brazilian Government expects an increase in mineral production by 2030 [67]. This will increase the pressure to exploit mineral reserves further, which increases threats to the existence of *A. glaziovii*. Mining has already been identified as the leading cause behind the irreversible loss of 40% of *canga* areas in the last 40 years [17]. For the next 50 years, forecasts indicate a catastrophic scenario for *cangas* [2]. Moreover, climate change could result in losses of up to 82%, and mining impacts could result in losses of up to 60% of the remaining areas of the *campos rupestres*. Therefore, although the forecasts obtained in our study indicate a suitable environment for

A. glaziovii's expansion, the speed of loss of the current occurrence areas of the species will hinder its survival until this natural expansion occurs.

5. Conclusions

The conservation status of the endangered microendemic species *Arthrocereus glaziovii* could change, as our models indicate an expansion in its future distribution. Unfortunately, this may not be the fate of the species.

Firstly, expansion is hindered because the species' occurrence areas are already under immense pressure from mining activities, and the future predicted occurrence areas of the species are already compromised due to mining. Secondly, climate change predictions specific to the *campos rupestres* indicate a catastrophic scenario for the *cangas,* resulting in losses of up to 82% of their areas [2]. The risk of species extinction is further exacerbated when considering that the loss and fragmentation of suitable areas could reduce genetic diversity within the species, making survival more difficult in the face of detected environmental changes. Additionally, the limited seed dispersal distance observed in endemic species from the *campos rupestres* could worsen the survival of *A. glaziovii*, which, for this species, could be more severe considering that germination rates are consistently below 50% [41,60].

The preservation of both the species and the ecosystems is urgent and imperative. We recommend community involvement and awareness for effective conservation by disseminating existing studies on the campos rupestres and its cacti. Additionally, the establishment of conservation units capable of safeguarding the areas and individuals of *A. glaziovii* from existing threats is paramount. Finally, further studies to aid the management and propagation of the species are urgently required, such as studies focused on the genetic diversity of its remaining populations, identification of seed propagation matrices, and restoration of degraded habitats to prevent the imminent extinction of this cactus.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/conservation4020011/s1, Table S1: Occurrence records of the specimens considered in the study; Table S2: Bioclimatic variables from the Worldclim database; Table S3: Edaphic variables (soil) from the IBGE database; Table S4: Edaphic correlation results in Minas Gerais, Brazil. Al—Aluminum, AlSat—Saturated Aluminum, BSat—Saturated Base, BSum—Sum Base, Ca—Calcium, Carb—Carbon, CEC—Cation exchange capacity, H—Hydrogen, K—Potassium, KCl—Potassium chloride, Mg—Magnesium, N—Nitrogen, Na—Sodium, OM—Organic Matter, WpH—pH Water; Table S5: Climatic correlation results in Minas Gerais, Brazil. BIO1 (annual mean temperature), BIO2 (mean diurnal range), BIO3 (isothermality), BIO4 (temperature seasonality), BIO5 (maximum temperature of warmest month), BI6 (minimum temperature of coldest month), BIO7 (temperature annual range), BIO8 (mean temperature of wettest quarter), BIO9 (mean temperature of driest quarter), BIO10 (mean temperature of warmest quarter), BIO11 (mean temperature of coldest quarter), BIO12 (annual precipitation), BIO13 (precipitation of wettest month), BIO14 (precipitation of driest month), BIO15 (precipitation seasonality), BIO16 (precipitation of wettest quarter), BIO17 (precipitation of driest quarter), BIO18 (precipitation of warmest quarter), BIO19 (precipitation of coldest quarter).

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References

1. IBRAM—Brazilian Mining Institute. Available online: https://www.ibram.org.br/ (accessed on 21 June 2019).
2. Fernandes, G.W.; Barbosa, N.P.U.; Alberton, B.; Barbieri, A.; Dirzo, R.; Goulart, F.; Guerra, T.J.; Morellato, L.P.C.; Solar, R. The deadly route to collapse and the uncertain fate of the rupestrian grasslands. *Biodivers. Conserv.* **2018**, *27*, 2587–2603. [CrossRef]
3. Cheib, A.L. Ecologia da Germinação e Potencial Para Formação de Banco de Sementes de Espécies de *Arthrocereus* A. Berger (Cactaceae) Endêmicas dos Campos Rupestres de Minas Gerais, Brasil. Master's Thesis, Universidade Federal de Minas Gerais, Belo Horizonte, Brazil, 2009.
4. Giulietti, A.M.; Pirani, J.R.; Harley, R.M. Espinhaço range region, eastern Brazil. In *Centres of Plant Diversity: A Guide and Strategy for Their Conservation, The Americas, Vol. 3*, 1st ed.; Davis, S.D., Heywood, V.H., Herrera-MacBryde, O., Villa-Lobos, J., Hamilton, A.C., Eds.; WWF/IUCN: Cambridge, UK, 1997; pp. 397–404.
5. Porto, M.L.; Silva, M.F.F. Tipos de vegetação metalófila em áreas da Serra de Carajás e de Minas Gerais, Brasil. *Acta Bot. Bras.* **1989**, *3*, 13–21. [CrossRef]
6. Jacobi, C.M.; Carmo, F.F. Diversidade dos campos rupestres ferruginosos no Quadrilátero Ferrífero, MG. *Megadiversidade* **2008**, *4*, 24–32.
7. Jacobi, C.M.; Carmo, F.F. Plantas Vasculares sobre Cangas. In *Diversidade Florística nas Cangas do Quadrilátero Ferrífero*, 1st ed.; Jacobi, C.M., Carmo, F.F., Eds.; Código Editora: Belo Horizonte, Brazil, 2012; pp. 31–42.
8. Fernandes, G.W. The megadiverse rupestrian grassland. In *Ecology and Conservation of Mountaintop Grasslands in Brazil*, 1st ed.; Fernandes, G.W., Ed.; Springer: Cham, Switzerland, 2016; pp. 3–14.
9. Silveira, F.A.O.; Negreiros, D.; Barbosa, N.P.U.; Buisson, E.; Carmo, F.F.; Carstensen, D.W.; Conceição, A.A.; Cornelissen, T.G.; Echternacht, L.; Fernandes, G.W.; et al. Ecology and evolution of plant diversity in the endangered campo rupestre: A neglected conservation priority. *Plant Soil* **2016**, *403*, 129–152. [CrossRef]
10. Buisson, E.; Le Stradic, S.; Silveira, F.A.O.; Durigan, G.; Overbeck, G.E.; Fidelis, A.; Fernandes, G.W.; Bond, W.J.; Hermann, J.M.; Mahy, G.; et al. Resilience and restoration of tropical and subtropical grasslands, savannas, and grassy woodlands. *Biol. Rev.* **2019**, *94*, 590–609. [CrossRef]
11. Fernandes, G.W. The shady future of the rupestrian grassland: Major threats to conservation and challenges in the Anthropocene. In *Ecology and Conservation of Mountaintop Grasslands in Brazil*, 1st ed.; Fernandes, G.W., Ed.; Springer: Cham, Switzerland, 2016; pp. 545–561.
12. Negreiros, D.; Fernandes, G.W.; Berbara, R.L.L.; Rodarte, L.H.O.; Barbosa, N.P.U. Caracterização físico-química de solos quartzíticos degradados e áreas adjacentes de campo rupestre na Serra do Cipó. *Neotrop. Biol. Conserv.* **2011**, *6*, 156–161. [CrossRef]
13. Ribeiro, R.C.; Figueiredo, M.L.N.; Picorelli, A.; Silveira, F.A.O. Limited seed dispersal distance in endemic species from tropical mountaintop grasslands may restrict upward migration in response to climate change. *Flora* **2023**, *298*, 152203. [CrossRef]
14. Jacobi, C.M.; Carmo, F.F. The contribution of ironstone outcrops to plant diversity in the Iron Quadrangle, a threatened Brazilian landscape. *AMBIO* **2008**, *37*, 324–326. [CrossRef]
15. IPCC [Intergovernmental Panel on Climate Change]. *Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the IPCC*; The Core Writing Team, Pachauri, R.K., Reisinger, A., Eds.; IPCC: Geneva, Switzerland, 2007; 104p.
16. Fernandes, G.W.; Barbosa, N.P.U.; Negreiros, D.; Paglia, A. Challenges for the conservation of vanishing megadiverse rupestrian grasslands. *Nat. Conserv.* **2014**, *12*, 162–165. [CrossRef]
17. Carmo, F.F. Importância Ambiental e Estado de Conservação dos Ecossistemas de Cangas no Quadrilátero Ferrífero e Proposta de Áreas-Alvo para a Investigação e Proteção da Biodiversidade em Minas Gerais. Master's Thesis, Universidade Federal de Minas Gerais, Belo Horizonte, Brazil, 2010.
18. Costa, M.A.; Rios, F.J. The gold mining industry in Brazil: A historical overview. *Ore Geol. Rev.* **2022**, *148*, 105005. [CrossRef]
19. Lobato, L.M.; Ribeiro-Rodrigues, L.C.; Zucchetti, M.; Noce, C.M.; Baltazar, O.F.; Silva, L.C.; Pinto, C.P. Brazil's premier gold province. Part I: The tectonic, magmatic, and structural setting of the Archean Rio das Velhas greenstone belt, Quadrilátero Ferrífero. *Miner. Depos.* **2001**, *36*, 228–248. [CrossRef]
20. Jacobi, C.M.; Carmo, F.F.; Campos, I.C. Soaring extinction threats to endemic plants in Brazilian metal-rich regions. *AMBIO* **2011**, *40*, 540–543. [CrossRef] [PubMed]
21. Fernandes, G.W.; Arantes-Garcia, L.; Barbosa, M.; Barbosa, N.P.U.; Batista, E.K.L.; Beiroz, W.; Resende, F.M.; Abrahão, A.; Almada, E.D.; Alves, E.; et al. Biodiversity and ecosystem services in the campo rupestre: A road map for the sustainability of the hottest Brazilian biodiversity hotspot. *Perspect. Ecol. Conserv.* **2020**, *18*, 213–222. [CrossRef]
22. Negreiros, D.; Fernandes, G.W.; Silveira, F.A.O.; Chalub, C. Seedling growth and biomass allocation of endemic and threatened shrubs of rupestrian fields. *Acta Oecologica* **2009**, *35*, 301–310. [CrossRef]
23. Zappi, D.; Taylor, N.; Silva, S.R.; Machado, M.; Moraes, E.M.; Calvente, A.; Cruz, B.; Correia, D.; Larocca, J.; Assis, J.G.A.; et al. *Plano de Ação Nacional Para a Conservação das Cactaceas*, 1st ed.; Instituto Chico Mendes de Conservação da Biodiversidade, ICMBio: Brasília, Brazil, 2011; pp. 1–58.
24. REFLORA—Plantas do Brasil: Resgate Histórico e Herbário Virtual Para o Conhecimento e Conservação da Flora Brasileira. Available online: http://floradobrasil.jbrj.gov.br/reflora/floradobrasil/FB1417 (accessed on 21 June 2019).

25. Ortega-Baes, P.; Sühring, S.; Sajama, J.; Sotola, E.; Alonso-Pedano, M.; Bravo, S.; Godínez-Alvarez, H. Diversity and Conservation in the Cactus Family. In *Desert Plants: Biology and Biotechnology*; Ramawat, K.G., Ed.; Springer: Berlin/Heidelberg, Germany, 2009; pp. 157–173.
26. Santos, M.R. *Cacti: Ecology, Conservation, Uses and Significance*; Nova Science Publishers Inc.: New York, NY, USA, 2019; 280p.
27. Gonzaga, D.R.; Souza, M.A.; Neto, L.M.; Peixoto, A.L.; Mendonça, C.B.F.; Gonçalves-Esteves, V. The systematic value of pollen morphology in *Arthrocereus* A. Berger (*Cactaceae, Cactoideae*). *Rev. Palaeobot. Palynol.* **2019**, *269*, 33–41. [CrossRef]
28. Zappi, D.C.; Taylor, N.P. Cactaceae. In *Diversidade Florística nas Cangas do Quadrilátero Ferrífero*, 1st ed.; Jacobi, C.M., Carmo, F.F., Eds.; Código Editora: Belo Horizonte, Brazil, 2012; pp. 98–100.
29. The IUCN Red List of Threatened Species. Available online: https://www.iucnredlist.org/search?query=Arthrocereus%20glaziovii&searchType=species (accessed on 22 July 2019).
30. Jacobi, C.M.; Carmo, F.F.; Vincent, R.C.; Stehmann, J.R. Plant communities on the ironstone outcrops—A diverse and endangered Brazilian ecosystem. *Biodivers. Conserv.* **2007**, *16*, 2185–2200. [CrossRef]
31. Skirycz, A.; Castilho, A.; Chaparro, C.; Carvalho, N.; Tzotzos, G.; Siqueira, J.O. Canga biodiversity, a matter of mining. *Front. Plant Sci.* **2014**, *5*, 1–9. [CrossRef]
32. King, L.C. A geomorfologia do Brasil Oriental. Rio de Janeiro. *Rev. Bras. Geogr.* **1956**, *18*, 147–265.
33. Stannard, B.L.; Harvey, Y.B.; Harley, R.M. *Flora of the Pico das Almas: Chapada Diamantina—Bahia, Brazil*, 1st ed.; Royal Botanic Gardens: London, UK, 1995; pp. 1–853.
34. Alvares, C.A.; Stape, J.L.; Sentelhas, P.C.; Gonçalves, J.L.M.; Sparovek, G. Köppen's climate classification map for Brazil. *Meteorol. Z.* **2013**, *22*, 711–728. [CrossRef]
35. Gianotti, A.R.C.; Souza, M.J.H.; Machado, L.M.; Pereira, I.M.; Vieira, A.D.; Magalhães, M.R. Análise microclimática em duas fitofisionomias do cerrado no alto Vale do Jequitinhonha, Minas Gerais. *Rev. Bras. Meteorol.* **2013**, *28*, 246–256. [CrossRef]
36. Lima, L.R.; Pirani, J.R. O gênero *Croton* L. (*Euphorbiaceae*) na Cadeia do Espinhaço, Minas Gerais, Brasil. *Bol. Bot.* **2003**, *21*, 299–344. [CrossRef]
37. IBRAM—Instituto Brasileiro de Mineração. Minério de Ferro. *Informações Sobre Economia Mineral Brasileira*, 1st ed.; Rodrigues, C.P., Costa, E.R., Eds.; Instituto Brasileiro de Mineração: Brasília, Brazil, 2015; pp. 22–25.
38. Bianchetti, M. *Vale Contabiliza Recuo de 41.2% na Extração de Minério em MG*; Diário do Comércio: Belo Horizonte, Brazil; Available online: https://diariodocomercio.com.br (accessed on 20 January 2021).
39. GBIF Occurrence Download. Available online: https://doi.org/10.15468/dl.smu5d3 (accessed on 21 July 2023). [CrossRef]
40. *Species*Link. Available online: https://specieslink.net/ (accessed on 13 January 2019).
41. Clímaco, L.F.S. Variabilidade Fenotípica da Espécie Microendêmica *Arthrocereus glaziovii* Zappy & Taylor (*Cactaceae*) em Campos Rupestres Ferruginosos. Master's Thesis, Universidade Federal de Ouro Preto, Ouro Preto, Brazil, 2017.
42. Hijmans, R.J.; Cameron, S.E.; Parra, J.L.; Jones, P.G.; Jarvis, A. Very high resolution interpolated climate surfaces for global land areas. *Int. J. Climatol.* **2005**, *25*, 1965–1978. [CrossRef]
43. Worldclim. 2020. Available online: http://www.worldclim.org (accessed on 15 May 2019).
44. Arruda, D.M.; Fernandes-Filho, E.I.; Solar, R.R.; Schaefer, C.E. Combining climatic and soil properties better predicts covers of Brazilian biomes. *Sci. Nat.* **2017**, *104*, 32. [CrossRef]
45. Hijmans, R.J.; Etten, J.V. Raster: Geographic Analysis and Modeling with Raster Data. R Package Version 2.0-12. 2012. Available online: http://CRAN.R-project.org/package=raster (accessed on 20 December 2022).
46. R Core Team. R: A Language and Environment for Statistical Computing. 2017. Available online: https://www.R-project.org/ (accessed on 15 February 2023).
47. Dormann, C.F.; Elith, J.; Bacher, S.; Buchmann, C.; Carl, G.; Carré, G.; Marquéz, J.R.G.; Gruber, B.; Lafourcade, B.; Leitão, P.J.; et al. Collinearity: A review of methods to deal with it and a simulation study evaluating their performance. *Ecography* **2013**, *36*, 027–046. [CrossRef]
48. Genuer, R.; Poggi, J.M.; Malot, T.M. VSURF: Variable Selection Using Random Forests. R Package Version 1.0.4. 2018. Available online: https://CRAN.R-project.org/package=VSURF (accessed on 20 December 2022).
49. Booth, T.H.; Nix, H.A.; Busby, J.R.; Hutchinson, M.F. BIOCLIM: The first species distribution modelling package, its early applications and relevance to most current MAXENT studies. *Divers. Distrib.* **2014**, *20*, 1–9. [CrossRef]
50. Carpenter, G.; Gillison, A.N.; Winter, J. Domain: A flexible modelling procedure for mapping potential distributions of plants and animals. *Biodivers. Conserv.* **1993**, *2*, 667–680. [CrossRef]
51. Phillips, S.J.; Anderson, R.P.; Schapire, R.E. Maximum entropy modeling of species geographic distributions. *Ecol. Model.* **2006**, *190*, 231–259. [CrossRef]
52. Elith, J.; Phillips, S.J.; Hastie, T.; Dudik, M.; Chee, Y.E.; Yates, C.J. A statistical explanation of MaxEnt for ecologists. *Divers. Distrib.* **2011**, *17*, 43–57. [CrossRef]
53. Breiman, L. Random Forests. *Mach. Learn.* **2001**, *45*, 5–32. [CrossRef]
54. Hijmans, R.J.; Phillips, S.; Leathwick, J.; Elith, J. Dismo: Species Distribution Modeling. R Package Version 1.3-14. Available online: https://CRAN.R-project.org/package=dismo (accessed on 3 July 2023).
55. Liaw, A.; Wiener, M. Classification and Regression by Randomforest. *R News* **2002**, *2*, 18–22.
56. Instituto Pristino's Geoenvironmental Digital Atlas Database. Available online: https://www.institutopristino.org.br (accessed on 20 December 2019).

57. Petit, S. The reproductive phenology of three sympatric species of columnar cacti on Curaçao. *J. Arid. Environ.* **2001**, *49*, 521–531. [CrossRef]
58. Lima, A.L.A. Padrões Fenológicos de Espécies Lenhosas e Cactáceas em Uma Área do Semi-Árido do Nordeste do Brasil. Master's Thesis, Universidade Federal Rural de Pernambuco, Recife, Brazil, 2007.
59. Alencar, J.C.; Almeida, R.A.; Fernandes, N.P. Fenologia de espécies florestais em floresta tropical úmida de terra firme na Amazônia Central. *Acta Amaz.* **1979**, *9*, 163–198. [CrossRef]
60. Oliveira, D.V. Aspectos da História de Vida de *Arthrocereus glaziovii* (K.Schum.) N.P.Taylor & Zappi (*Cactaceae*), uma Espécie Endêmica do Quadrilátero Ferrífero, Minas Gerais, Brasil. Master's Thesis, Universidade Federal de Ouro Preto, Ouro Preto, Brazil, 2017.
61. Cheib, A.L.; Garcia, Q.S. Longevity and germination ecology of seeds of endemic Cactaceae species from high-altitude sites in southeastern Brazil. *Seed Sci. Res.* **2012**, *22*, 45–53. [CrossRef]
62. Gonçalves, L.N. Campos de altitude do maciço Marins-Itaguaré, Serra da Mantiqueira SP/MG: Composição Florística, Fitogeografia e Estrutura da Vegetação. Master's Thesis, Universidade Federal de Juíz de Fora, Juíz de Fora, Brazil, 2019.
63. Sá Júnior, A. Aplicação da Classificação de Köppen Para o Zoneamento Climático do Estado de Minas Gerais. Master's Thesis, Universidade Federal de Lavras, Lavras, Brazil, 2009.
64. Costa, S.A.D. Caracterização Química, Física, Mineralógica e Classificação de solos ricos em ferro do Quadrilátero Ferrífero. Ph.D. Thesis, Universidade Federal de Viçosa, Viçosa, Brazil, 2003.
65. Souza, V.N.R.; Neto, J.E.E.; Matrangolo, C.A.R.; Magalhães, W.T.; Fogaça, C.A.; Figueiredo, M.A.P.; Figueiredo, L.H.A. Caracterização de diferentes solos eutróficos na região norte de Minas Gerais. *Rev. Intercâmbio* **2019**, *15*, 106–122.
66. Meira, R.M.S.A.; Peixoto, A.L.; Coelho, M.A.N.; Ponzo, A.P.L.; Esteves, V.G.L.; Silva, M.C.; Câmara, P.E.A.S.; Meira-Neto, J.A.A. Brazil's mining code under attack: Giant mining companies impose unprecedented risk to biodiversity. *Biodivers. Conserv.* **2016**, *25*, 407–409. [CrossRef]
67. *Plano Nacional de Mineração 2030. Geologia, Mineração e Transformação Mineral*; Ministério das Minas e Energia: Brasília, Brazil, 2010. Available online: https://www.gov.br/mme/pt-br/assuntos/secretarias/geologia-mineracao-e-transformacao-mineral/plano-nacional-de-mineracao-2030-1 (accessed on 23 June 2019).